NASA
Technical Memorandum 83476

AVRADCOM
Technical Report 83-C-7

Detailed Fuel Spray Analysis Techniques

(NASA-TM-83476) DETAILED FUEL SPRAY ANALYSIS TECHNIQUES (NASA) 23 p HC A02/MF A01 CSCL 21E
N83-34943
Unclas
G3/07 42054

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Prepared for the
Sixty-second Symposium of the Propulsion and Energetics Panel
on Combustion Problems in Turbine Engines
sponsored by AGARD
Cesme, Turkey, October 3-6, 1983

NASA

E-1792

DETAILED FUEL SPRAY ANALYSIS TECHNIQUES

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SUMMARY

Detailed fuel spray analyses are a necessary input to the analytical modeling of the complex mixing and combustion processes which occur in advanced combustor systems. It is anticipated that by controlling fuel-air reaction conditions, combustor temperatures can be better controlled, leading to improved combustion system durability. Thus, a research program is underway to demonstrate the capability to measure liquid droplet size, velocity, and number density throughout a fuel spray and to utilize this measurement technique in laboratory benchmark experiments. The research activities from two contracts and one grant are described with results to date. The experiment to characterize fuel sprays is also described. These experiments and data should be useful for application to and validation of turbulent flow modeling to improve the design systems of future advanced technology engines.

INTRODUCTION

The economic pressures that face all of us today are also having a dramatic effect on the aircraft industry, commercial airlines, and the military. In the area of propulsion, the development costs to evolve a new engine for the next generation aircraft are becoming staggering. And in the interest of fuel economy, new engines are operating at higher pressures and temperatures which can adversely affect the operating and maintenance costs of the hot section components. This situation is placing greater demands on the engine designer to produce a dependable and reliable system. This is especially true with the combustor, where fuel and air must be efficiently mixed and where combustion must take place in a minimum amount of space. It is perceived that a better understanding of the complex mixing and combustion processes which occur in a combustor could reduce the time required to design and develop new combustor concepts, and could also lead to more optimized designs resulting in improved component durability. It is for these benefits that the National Aeronautics and Space Administration's Lewis Research Center (LeRC) is engaged in combustion research. The objective of the research is to obtain a better understanding of these physical processes and to develop analytical models which can accurately describe these processes.

The current combustion program at LeRC is organized into two categories; combustion fundametals research and applied combustion research. Research activities under the combustion fundamentals category are classifed under the subject areas of fuel sprays, mixing, radiation/chemistry, and combustion dynamics, figure 1. Each of these subject areas have research activities to develop and improve analytical models and to perform experiments to better understand the physical processes and provide needed data for the modelers,

references 1, 2. As shown in figure 2, the long range objective is to obtain predictive computer codes which the industry can utilize in their combustion design system. The remainder of this paper will focus on the experimental research activities in the subject area of fuel sprays.

A great deal of research, both experimental and analytical, had addressed itself to the problem of spray combustion. A liquid fuel spray undergoes vaporization and mixing with a turbulent airstream just prior to the combustion process. The relative velocities between the fuel's gas phase and liquid droplets affect the evaporation, burning rate, and the pollutant formation. In attempts to analytically model this two-phase flow, detailed information on the fuel spray and air boundary conditions are required, reference 3 and 4. Furthermore, assessments of the analytical models require detailed information of the fuel spray throughout the spray cone, reference 5. Thus, it is necessary to measure the size and velocity distribution of the spray droplets and the evolution of their distributions with the flow.

Several laser measurement methods can provide the required data in principle, references 6 and 7, and large strides in the area of laser velocimetry and signal processing have been made in recent years to improve these techniques. As part of the combustion research program, LeRC is conducting a program to demonstrate the capability to measure liquid droplet size, velocity, and number density throughout a fuel spray and to utilize this instrument in laboratory benchmark experiments to obtain the required data for the analytical models. This program is described below. In addition, two contracts are underway to further refine droplet sizing interferometer techniques. The Advanced Droplet Sizing System incorporates two similar but distinct techniques to use scattered laser light to determine particle size and velocity. The Phase Detection Droplet Sizing System also uses scattered laser light, but compares the phase differences at two points to determine particle size. These promising systems are highlighted with results to date presented. Finally, it is recognized that applying instruments such as these to reacting and non-reacting fuel sprays presents a formidable task of data processing and analysis. An effort is underway which focuses on further development of these analysis techniques. A co-axial free jet apparatus is being built to study the combustion parameters of a relatively simple liquid fuel spray combustion process. Modern diagnostic instruments will be utilized to establish data analysis procedures and provide experimental data for analytical model assessment. This research activity is described.

NASA LeRC FUEL SPRAY DIAGNOSTICS PROGRAM

The Fuel Spray Diagnostics Program is a part of the LeRC Combustion Fundamentals Research, references 1 and 2. The objective of this in-house program is to conduct detailed investigations of fuel and air mixing downstream of fuel nozzles in order to supply the analytical modeler with needed benchmark data for model assessment. Measurements of droplet size and velocity at conditions representing those of gas turbines are required. A knowledge of the turbulent interactions between flowing air streams and simulated fuel sprays is also necessary; thus measurements of air velocity are made simultaneously with the droplet measurements to completely track the flow characteristics.

This experimental research is being conducted in the Fuel Spray Diagnostics Facility. The major instrument used is a Droplet Sizing Interferometer (DSI). A photograph of the existing experimental configuration is presented in figure 3. The DSI is a two-color, two-component system. Two independent,

orthogonal measurements of droplet size and velocity components can be made simultaneously. The transmitter unit includes a 0.5 watt Argon ion laser. Two receivers, situated at different angles, measure the horizontal and vertical components. A water spray from a fuel nozzle is probed throughout with the DSI instrument to determine nozzle characteristics. The apparatus will be discussed in more detail in the following section.

The Fuel Spray Diagnostics Program consists of various experimental configurations, presented in Table I. In the first part, water will be used to simulate fuel sprays. Several test conditions and probe volume positions for mapping typical fuel nozzle flow distribution will be selected. The second part will utilize a fuel nozzle/swirler combination to study fuel/air mixing characteristics and flow seeding. Finally, measurements of more complex turbulent fuel spray chemical reaction flows are planned for analytical application to the combustion process.

DROPLET SIZING INTERFEROMETER

The existing NASA LeRC Droplet Sizing Interferometer (DSI) is a laser based instrument currently being developed for application to dense sprays. The instrument is used for measuring liquid droplets and solid particles in fluid flows. The measurement of droplet (or particle) size and velocity is based upon the observations of light scattered by small particles passing through the crossover region of two laser beams. The off-axis light scatter detection method is used in the size and velocity measurements; droplets are treated as spheres that reflect or refract light, references 8, 9.

The DSI can operate in most spray and aerosol environments to provide size and velocity measurements to a high degree of accuracy. It is also capable of obtaining large quantities of spray data in a small time. There is an urgent need of such data to properly define the physical characteristics of two phase flows essential to many engineering applications in combustion systems.

The fundamental features of the instrument are: optics, signal processing, and data management system. The optical system contains two packages that are very critical in the accuracy of the measurements, the transmitter and the receiver. Figure 4 shows the basic configuration of the droplet sizing optical system for single component measurements. The transmitting optics define two parameters, the fringe spacing (determined by the crossover angle of the laser beam) and the position of the probe volume. It is composed of a 0.5 watt Argon Ion laser, beam expander, beam splitter and focusing lens. The laser is used to provide a coherent light source to non-intrusively measure small droplet size and velocity. A beam expander consists of two lenses placed focal point to focal point where the diameter of the laser beam can be increased as necessary. The beam splitter produces two exit beams of approximately equal intensity and is used to adjust the separation between them. The beams are then intersected by focusing them with a lens. The probe volume or point of intersection of the laser beams forms an interference pattern of fringes, figure 5(a). Droplets passing through these fringes project scattered light with different patterns that are used in the measurement of size and velocity. The receiving optics collect the light scattered from droplets moving through the probe volume. It contains a collecting lens and a photomultiplier (PMT). The collecting lens is used to image the probe volume on the photomultiplier's aperture or pinhole, where the droplet signals are registered.

The signal processing components are enclosed in a Visibility Processor. It consists of Signal Filtering, Percentage of Error Setting, Doppler Integrators, Pedestal Integrators and also controls a programmable power supply that

generates the high voltage for the photomultiplier tube. The Visibility Processor is mainly used to process doppler burst signals. The input signals to the processor are doppler signals superimposed on Gaussian pedestals, figure 5(b). The processor separates the doppler component from the pedestal component. The droplet size is determined from the signal visibility (that is the magnitude of the ratio between the Doppler and the pedestal components) and the velocity from the Doppler frequency.

The Data Management System (DMS) is a microprocessor that collects, stores and analyzes data. It acquires raw data from the Visibility Processor. The DMS contains data display and acquisition programs with histograms of the visibility and period distributions. Floppy disks are used for software and data storage. A printer-plotter is included to provide hard copy records.

ADVANCED DROPLET SIZING SYSTEM

Two advanced techniques for the measurement of the size and velocity of particles will be incorporated in the original Droplet Sizing Interferometer to eliminate some of the problems encountered in the real environment situations. This new instrument is the Advanced Droplet Sizing System (ADSS) and the referred techniques are: the Visibility Intensity Technique (V/I) and the Intensity Maximum technique (IMAX).

The Advanced Droplet Sizing System will be designed to be a modular type that includes the two combined measurement techniques. This design concept provides the system with capabilities for future expansions based on results of new developments in the research of light scattered methods. The research is being done under a NASA contract with Spectron Development Laboratories, Inc. and the principal investigator is Dr. Cecil F. Hess.

Limitations of Light Scatter Measuring Methods

Light scatter methods were developed with the intention of obtaining large quantities of significant particle measurements in a reasonable amount of time. Since the concept of visibility for particle sizing was introduced, many studies have been carried out in the development of this technology. However, limitations surface when these methods are applied to real environments.

The main limitation of the visibility technique, where the visibility of a doppler signal is used as a sizing parameter, is its incapability to measure particles in a dense field. In environments like dense sprays and turbulent media, particles appear to be larger due to the presence of multiple particles in the probe volume. Also, the fringe pattern at the probe volume is affected by particles intersecting the laser beams. An inaccurate visibility magnitude can result from various other causes, e.g. loss of fringe contrast due to imperfections in optical components, dependency on where the particle goes through probe volume, misalignment and increase in background noise due to small drops present in probe volume. Some of these limitations can be eliminated after they are recognized, but the most difficult ones are those due to the real environment situations.

The Visibility/Intensity (V/I) Technique

The V/I technique is based on the visibility and intensity of the scattered light signal to obtain the size and velocity of individual droplets. It is known that the relationship between visibility and size is not straight forward in real environments. The V/I technique, reference 10, eliminates

some of the errors produced by measuring dense sprays. It uses the intensity of the pedestal of the scattered light in addition to the visibility. The signal from each particle produces both parameters and their cross-correlation can be used to select the right signals.

A correlation between the measured size of the droplet and the amount of scattered light (Mie theory) is used to eliminate signals that indicate the wrong size. This technique is based on the fact that droplets that produce certain visibility must have a given size, and consequently they must scatter light with a given intensity. In this manner, limits are fixed for every measured visibility.

Two of the main problems are solved by this technique. First, droplets with erroneous visibility (due to beam blockage that causes a disturbed probe volume) will scatter light with an intensity lower than the one pertaining to their apparent size. Second, droplets crossing the probe volume at the point of less intensity (the tail of the Gaussian intensity profile) will have the right visibility, but will scatter light with different intensity. The V/I technique sets limits for the probe volume and rejects invalid signals by establishing limits on the intensity of the pedestal, figure 6.

An advantage of the V/I technique is that it does not require calibration. However, it is currently limited to a size range of about 10:1 in low density sprays and about 5:1 in denser sprays for each optical setting.

Intensity/Maximum (IMAX) Technique

The second technique used by the Advanced Droplet Sizing System is the Intensity Maximum technique. This technique uses the peak intensity of the pedestal to estimate the size.

The intensity of the laser beam has a Gaussian distribution, therefore, the intensity of the pedestal depends on where the particle crosses the laser beam in the probe volume. This technique establishes limits within the probe volume where a particle can cross. It eliminates the uncertainty caused by the Gaussian beam intensity distribution and makes use of the direct relationship between intensity and droplet size.

In order to establish the limits within the probe volume, two laser beams of different diameter are crossed as illustrated in figure 7. An interference pattern of fringes is formed in the crossover where the intensity is almost uniform in the big beam. Size and velocity measurements are obtained from the peak intensity of the pedestal of the large beam and the doppler frequency for each signal.

The advantages associated with this method are: size measurements performed in a region of uniform intensity and capability of velocity measurement and size range possibilities up to 30:1 with appropriate electronic processing. One limitation is the beam blockage, caused by dense sprays, that results in a reduction of intensity. However, this limitation is not as serious as in other techniques with a non-uniform intensity distribution at the probe volume.

Measurements with the V/I and IMAX Techniques

Some experiments are underway to evaluate and compare the capabilities of the V/I and IMAX techniques. The up to date results for the experiments that will be presented here are explained in more detail by Dr. C. F. Hess in reference 10.

The main limitation of the visibility technique, as was previously discussed, is its incapability to measure particles in a dense field. For this

reason, experiments focused on the effect of beam blockage on size distribution. Figure 8 shows the effect of obstructing the laser beams with a dense spray before the crossing point. The first histogram (fig. 8(a)) pertains to a monodispersed string of droplets crossing through the middle of the probe volume. The second histogram (fig. 8(b)) presents the measurements obtained with the Visibility technique when a dense spray is placed before the probe volume. The fringe pattern is altered, resulting in a false extended size distribution. The third histogram (fig. 8(c)) corresponds to the V/I technique, under the same circumstances. The size distribution in this case is very similar to the one generated in the absence of spray blockage (fig. 8(a)).

The effect of beam blockage on size distribution was also investigated using the IMAX technique. Results are shown in figure 9. The first histogram (fig. 9(a)) presents the size distribution of monodispersed droplets going through the probe volume. The second histogram (fig. 9(b)) corresponds to the results obtained with the IMAX technique when a spray is obstructing the laser beams in front of the probe volume. This technique also shows very favorable results, with the average diameter nearly the same, even though some corrections were found to be needed. The V/I and IMAX techniques are still being developed and all the measurements taken are in a preliminary stage. A final report will be published with the results of this program.

PHASE DETECTION DROPLET SIZING SYSTEM

Laser light scatter interferometry techniques offer potential for non-intrusive real-time measurements in relatively dense sprays. A schematic of a generic optical system for droplet sizing is shown in figure 4 and is based on laser doppler velocimetry principles. This system features off-axis light scatter detection which was first analyzed theoretically by Bachalo (ref. 8). A schematic of an alternate system based on phase detection of scattered fringe patterns is shown in figure 10. This system is currently undergoing breadboard evaluation by a contractor for NASA LeRC, namely, Aerometics, Inc. The principal investigator is Dr. W. D. Bachalo who has authored several papers on droplet sizing techniques, e.g. references 8 and 9.

The approach utilizes the fact that light deflected by a sphere through the mechanisms described by refraction and reflection theory can be measured and analyzed to obtain the diameter of the sphere passing through the intersection region of two laser beams. Light scattered from one beam will be shifted in phase with respect to the other by an amount that depends upon the angle of observation and the optical paths through the sphere. The scattered light will have an associated phase difference which produces an interference fringe pattern surrounding the spherical droplet (see fig. 10 inset). The spacing of the interference fringe pattern at some region in the space surrounding the droplet can be seen to be inversely proportional to the droplet diameter. Proper selection of a means for measuring the fringe spacing will result in a linear relationship between the measured quantity and the droplet size.

Using the proper configuration of two or more detectors will result in two or more identical Doppler burst signals that are shifted in phase (see fig. 11). This phase difference which can be measured accurately is linearly proportional to the droplet size.

Furthermore, when a droplet moves through the intersection of the laser beams, light scattered from each beam undergoes a doppler frequency shift. The scattered fringe pattern appears to move at the doppler difference frequency between the scattered light from each beam. Using the known beam intersection angle and the laser wavelength, the measured signal frequency

will produce an accurate meaurement of the droplet velocity. Thus, the same period information provides droplet velocity measurements as well as droplet size measurements. Both measurements are unaffected by beam attenuation provided that the signal-to-noise ratio is sufficient.

The relationships used to obtain the droplet size from the measured signal phase difference for the specified optical parameters are shown in figure 11. The significance of the result is that the instrument response is linear over the entire size range. The size range can be set easily by adjusting the beam intersection angle and the gain on the photodetectors.

Recent data samples from measurements of a monodisperse droplet stream produced by a Berglund-Liu generator are shown in figure 12. The size range corresponds to a phase difference range from 0 to 360 degrees divided into 72 bins of 5 degrees each. The data shown in figure 12(a) resulted in a measured mean droplet size of 125.9 μm compared to the calculated monodisperse stream size of 129.5 μm. The data shown in figure 12(b) were obtained while introducing an additional spray in the beam paths around the monodisperse droplet stream. These results are encouraging but further tests are planned to verify the technique with a variety of spray densities and a variety of spray droplet size distributions.

MEASUREMENT OF SPRAY COMBUSTION PARAMETERS

Historically, the precise measurement of spray combustion parameters has been precluded because of the lack of appropriate instrumentation techniques. However, with the recent development of the interferometric systems described above plus other laser-based diagnostics, fruitful experimental research on spray flames now appears possible. As a result LeRC has established a grant with the Gas Dynamics Research Division of the University of Tennessee Space Institute (UTSI) to utilize modern laser diagnostic techniques in making measurements of parameters in a relatively simple steady spray combustion process. The principal investigators for this project are Dr. Carroll Peters and Dr. Michael Farmer who have extensive experience in fluid mechanics and nonintrusive laser instrumentation. This three year research effort has two objectives. First, to develop well established procedures for making measurements in a typical spray combustion environment and for acquiring, processing, displaying and interpreting the voluminous data that are produced by the modern instrumentation systems. Second, to produce accurate experimental information that elucidates the fundamental mechanisms in spray combustion and that can be used to validate and refine analytical models of spray combustion. The techniques developed above, including specialized microcomputer hardware and software, will be applicable to the NASA LeRC Fuel Spray Diagnostics Program described above.

Experimental Apparatus

The experiments will be conducted with the specially designed coaxial free jet apparatus shown schematically in figure 13. The central droplet-air jet will be the exhaust from a plain-jet atomizer of the type investigated by Lorenzetto and Lefebvre, reference 1[illegible]. The diameter of the central nozzle will be about 1.3 cm, and the air-liquid massflow ratio will be about five. Therefore, for typical hydrocarbon fuel, the equivalence ratio of the central jet will be about three. For typical fuel properties, the central-jet atomizer will produce a Sauter mean diameter (SMD) of 60-70 μm at a nominal jet air velocity of 100 m/s.

The outer air flow will be varied, from velocities of zero to about 20 m/s. A recirculation zone will form at the blunt base of the center body (about 5 cm in diameter). For the combustion experiments, an igniter will be inserted into the recirculation region, which will be a flameholder for the spray flame.

The axisymmetric freejet apparatus was selected for two reasons. First, the apparatus provides the major features of typical spray combustion processes without the complexity of three-dimensional geometry. Second, the freejet configuration provides optical access to the entire flowfield.

Program Approach

After shakedown and calibration of the freejet apparatus, a series of droplet cloud experiments, without combustion, will be conducted. Measurements of the gas-phase velocity and turbulence field will be made with a two-component laser velocimetry system. Measurement of the droplet cloud parameters produced by the plain-jet atomizer will be made with the UTSI droplet sizing interferometer. Analytical studies of spray cloud dynamics will be carred out to aid in the interpretation of the results and to assess the dynamic interactions between the droplet cloud and the turbulent gaseous medium.

The freejet combustion apparatus will then be operated with an ignited spray of pure hydrocarbon fuel. Gas phase and droplet cloud parameters will be measured as above. Temperature and number density of major gaseous species in the hydrocarbon spray flame will be measured with a laser Raman system. A large number of measurements of the instantaneous properties will be made at each of many spatial stations in the spray flame in order to adequately define the statistical properties of the entire temperature and species field.

To date the coaxial freejet apparatus is being fabricated and the test facility built up. Initial experiments will be conducted in the fall of 1983. The initial and boundary conditions of the combustion experiments will be carefully defined so that the results can be used to evaluate systematically various aspects of the available numerical models of the spray combustion process.

Clearly, there is a need for careful experiments on the interaction between the dynamics of a cloud of droplets and the dynamics of the turbulent gaseous medium within the droplet cloud. Our goal is to produce a well-defined and well-controlled experiment that can be used for validation and refinement of numerical models of the entire spray combustion process.

CONCLUDING REMARKS

The advanced laser light scatter interferometry techniques described in this report show promise of providing improved capabilities for obtaining droplet size measurements and droplet velocity data in dense fuel sprays. Results to date have demonstrated that these techniques can be successfully applied to yield valuable data which are useful in modeling of combustion flow characteristics and dynamics. Fuel spray characterization, turbulence studies, and fuel-air reaction studies are highly important for predicting combustion performance. These research and development efforts are expected to provide a fundamental data base for turbulence model development and for an improved combustor design system.

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TABLE I. - FUEL SPRAY DIAGNOSTICS PROGRAM

Experiment description
• Spray characterization-H_2O -Various nozzle types -Pressure differential effects Size and velocity distribution -Several sampling planes
• Turbulence studies - seeded -Various air swirler configurations -Vane angle effects -Airflow splits
• Fuel-air reaction studies -Various equivalence ratios -Fuel property effects -Measure turbulence intensity

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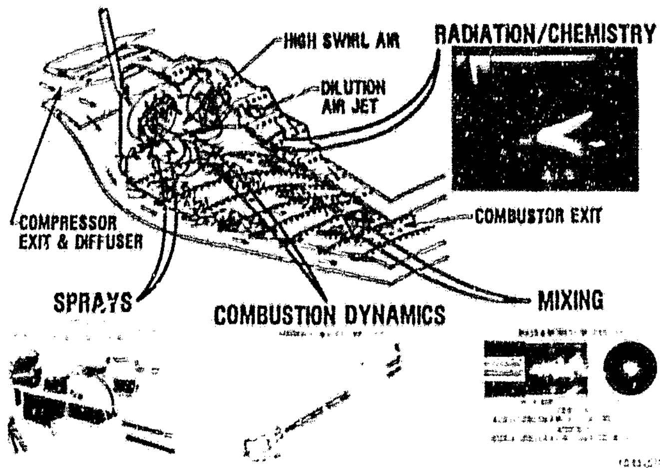

Figure 1. - Combustion fundamentals program at NASA Lewis Research Center is divided into four major subject areas: fuel sprays, mixing, radiation/chemistry, and combustion dynamics.

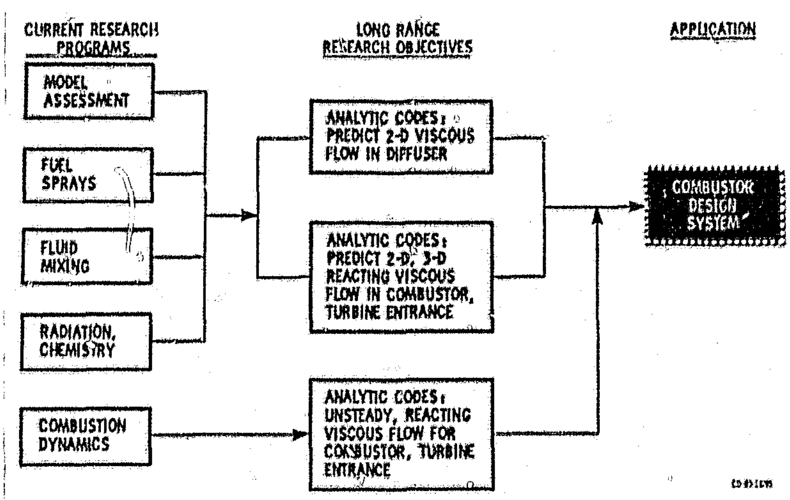

Figure 2. - Combustion fundamentals research has long range objectives to produce predictive analytic computer codes that have practical application in engine manufacturer's combustion design system.

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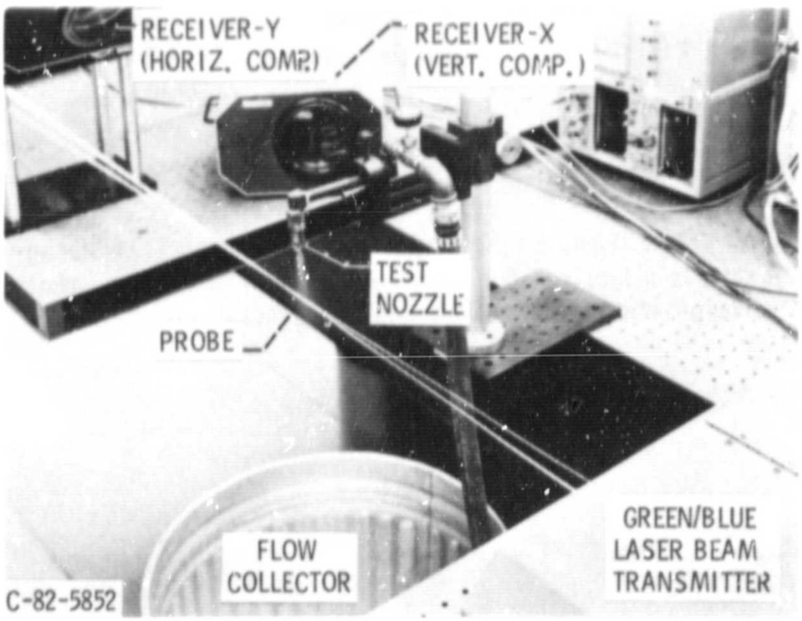

Figure 3. - Photograph of the existing two-component Droplet Sizing Interferometer (NASA LeRC).

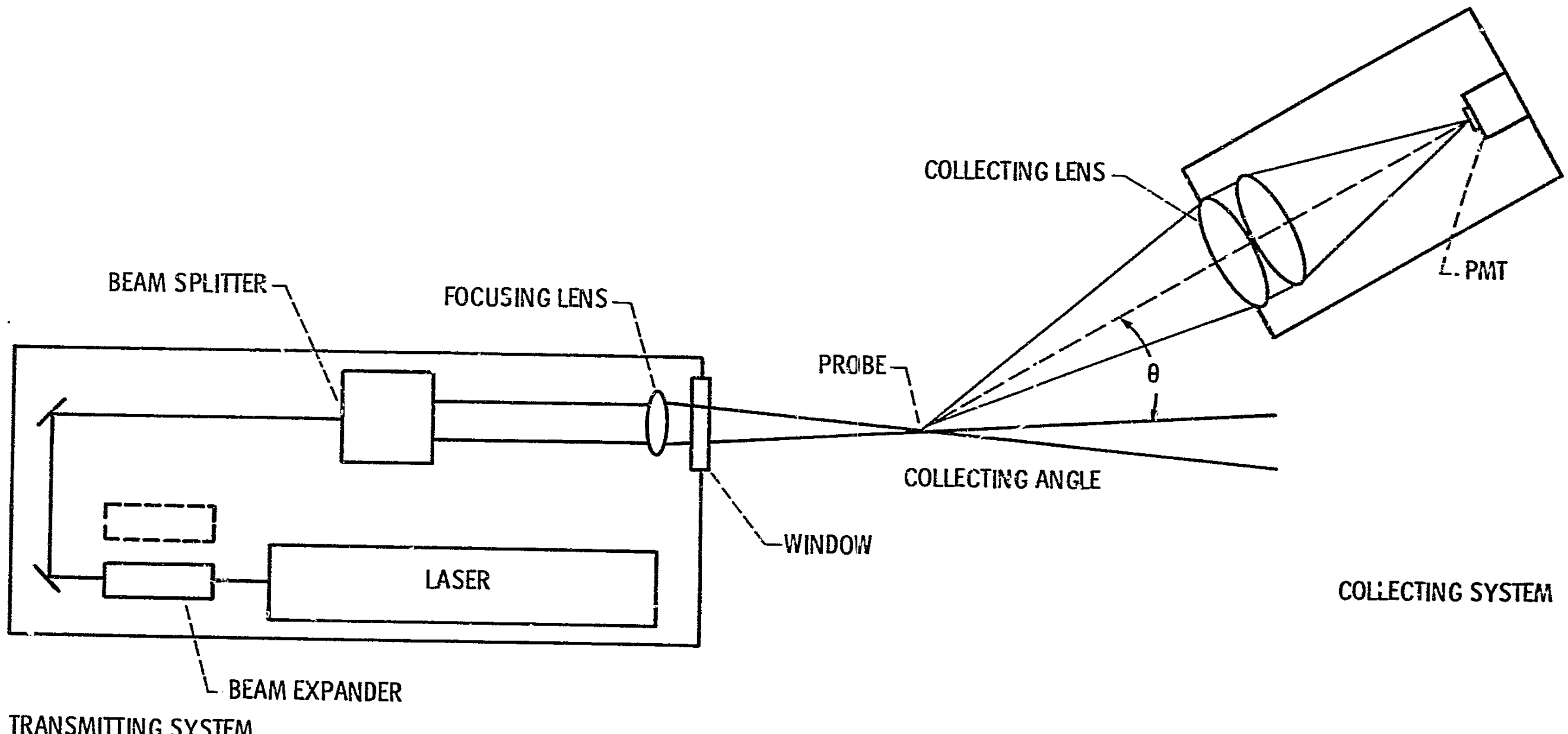

Figure 4. - System diagram of optical configuration for droplet sizing interferometer.

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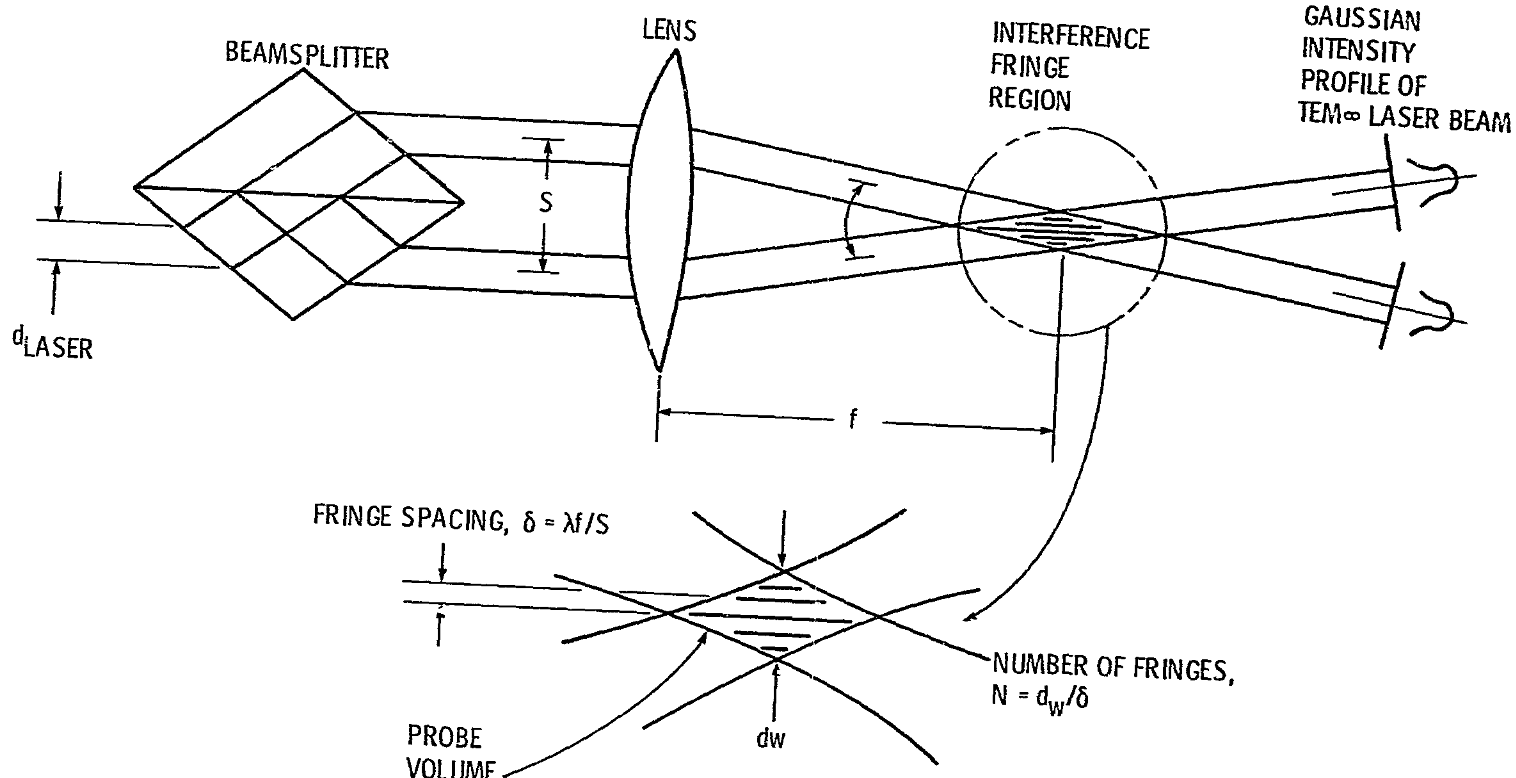

(a) Formation of fringes in the probe volume.

Figure 5. - Droplet sizing interferometer optics and signal processing.

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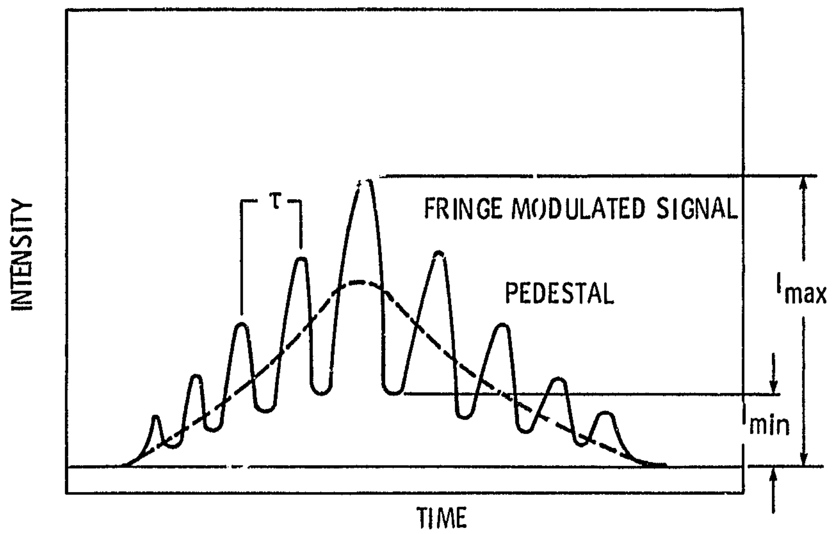
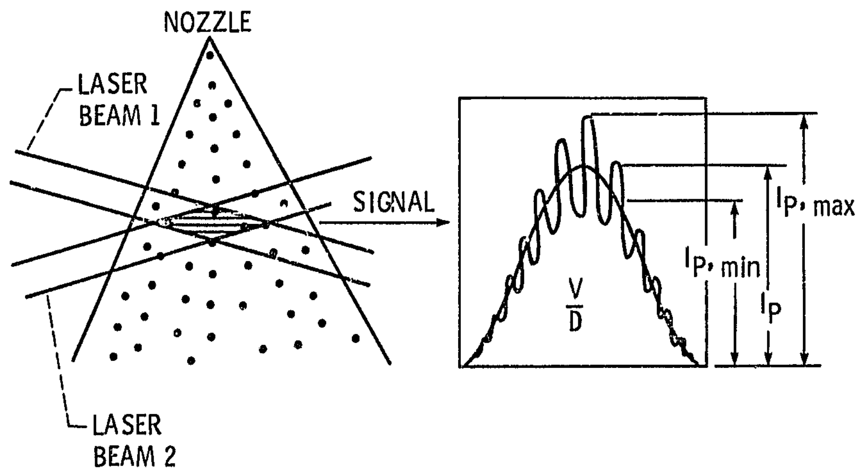


(b) Doppler burst signal with the Doppler and pedestal components.

Figure 5. - Concluded.



(a) Spray going through the fringes produced at the crossing point of two laser beams.

(b) Doppler burst signal with the intensity limits.

Figure 6. - Schematic representation of the visibility/intensity technique.

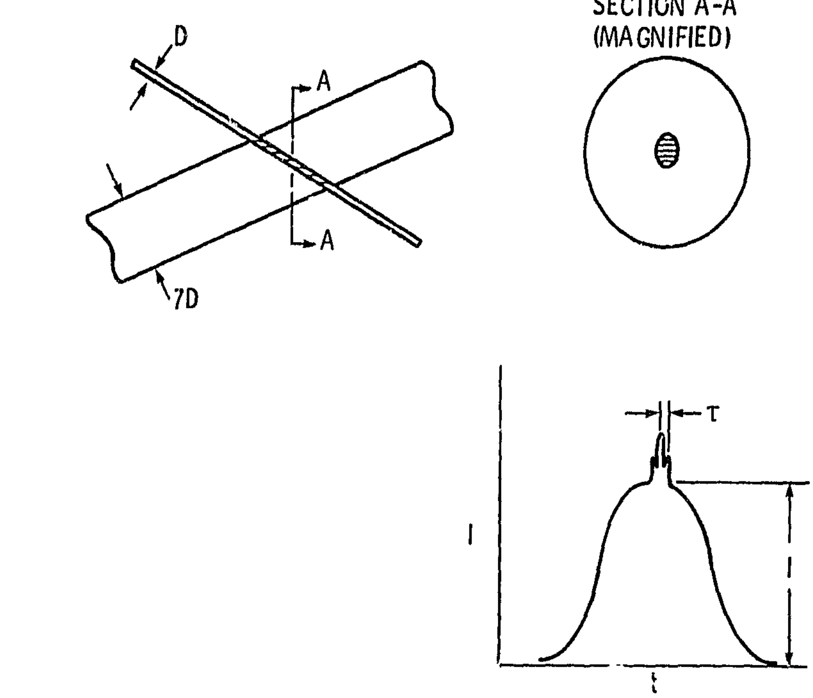
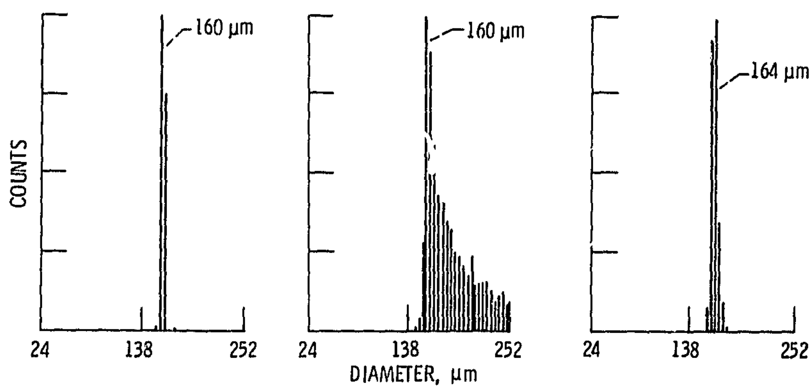


Figure 7. - Optical configuration, probe volume and Doppler burst signal as described by the intensity maximum technique.

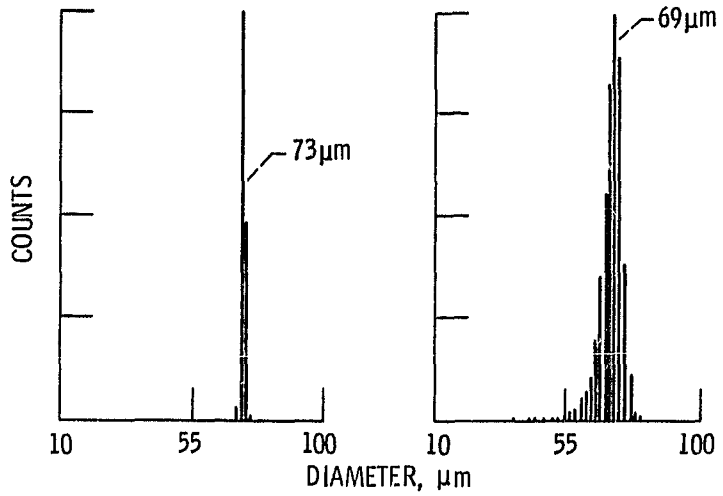


(a) Visibility or v/I measurements of monodispersed droplets with undisturbed laser beams.

(b) Visibility measurements of monodispersed droplets with dense spray blocking the laser beams before crossing.

(c) Visibility/intensity measurements of monodispersed droplets with dense spray blocking the laser beams before crossing.

Figure 8. - Size distribution of a monodispersed string of droplets using the visibility and visibility/intensity techniques.



(a) Intensity/maximum measurements of monodispersed droplets with undisturbed laser beams.

(b) Intensity/maximum measurements of monodispersed droplets with dense spray blocking the laser beams before crossing.

Figure 9. - Size distribution of a monodispersed string of droplets using the intensity/maximum technique.

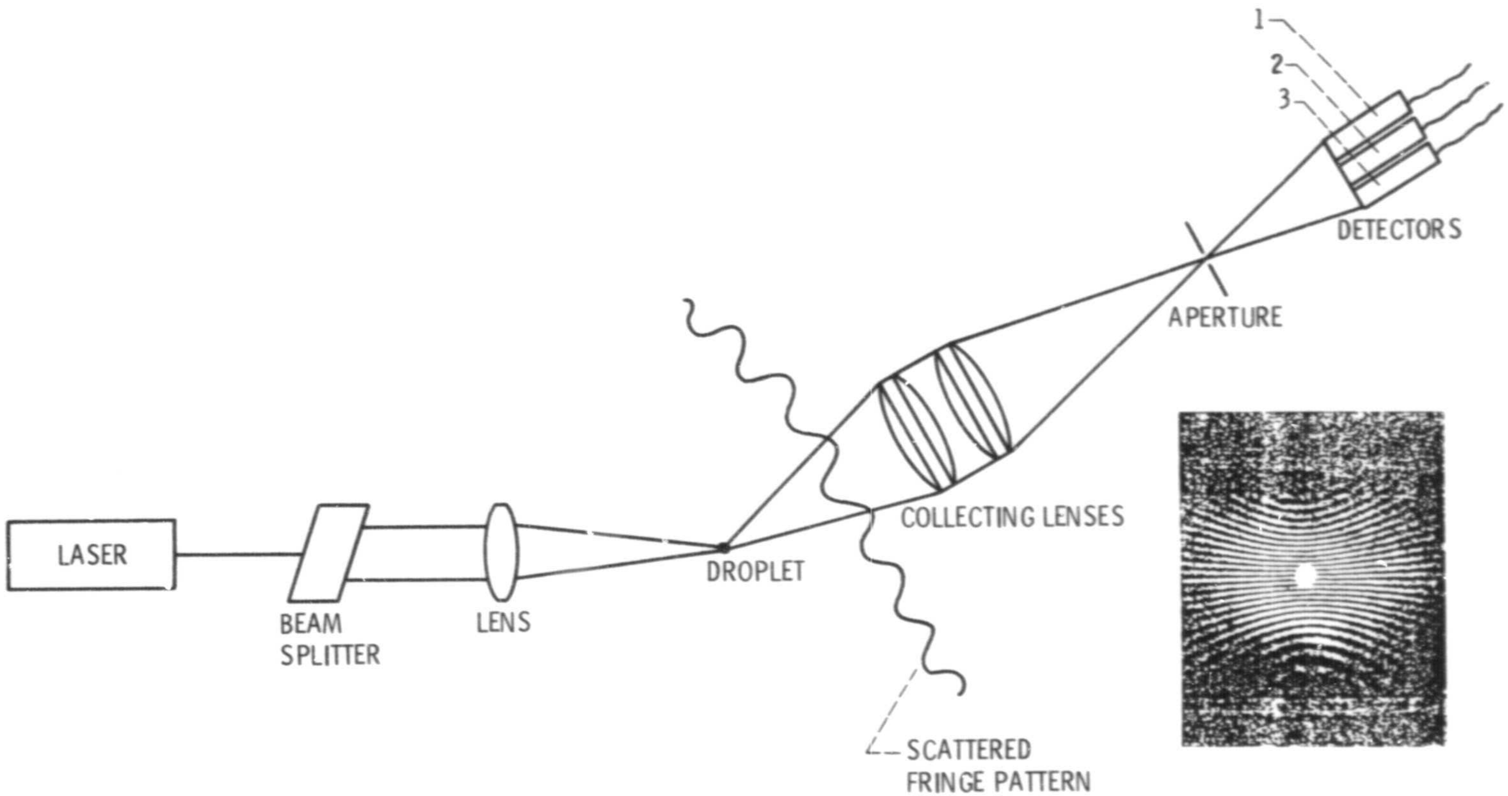


Figure 10. - Schematic representation of phase detection optical system with photograph of scattered interference fringes.

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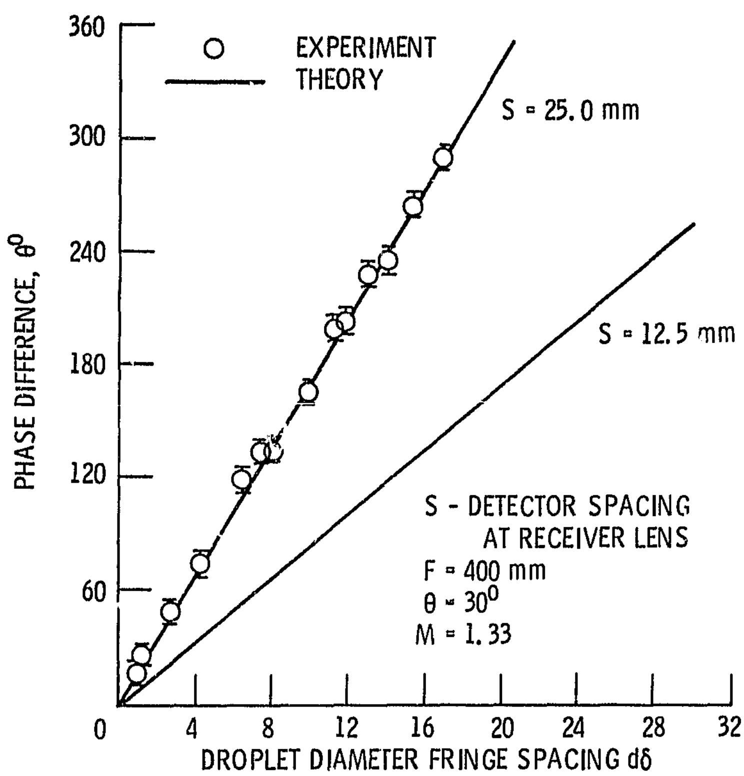

Figure 11. - Relationship of measured phase difference with nondimensional size ratio; experimental data compared to theoretical predictions.

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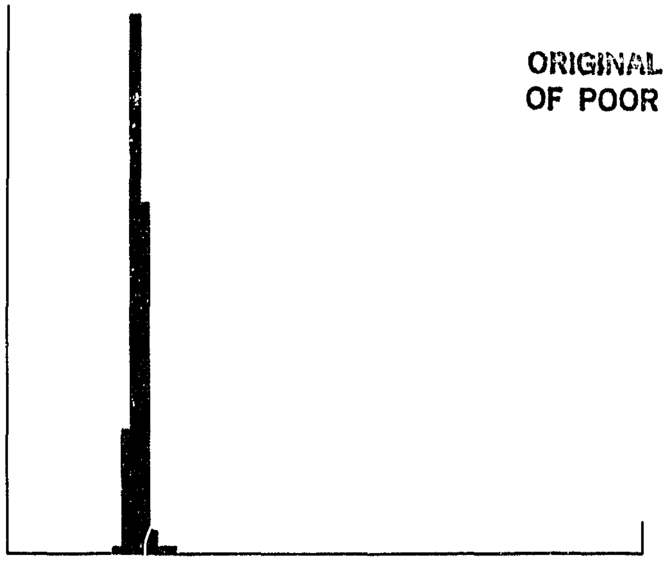
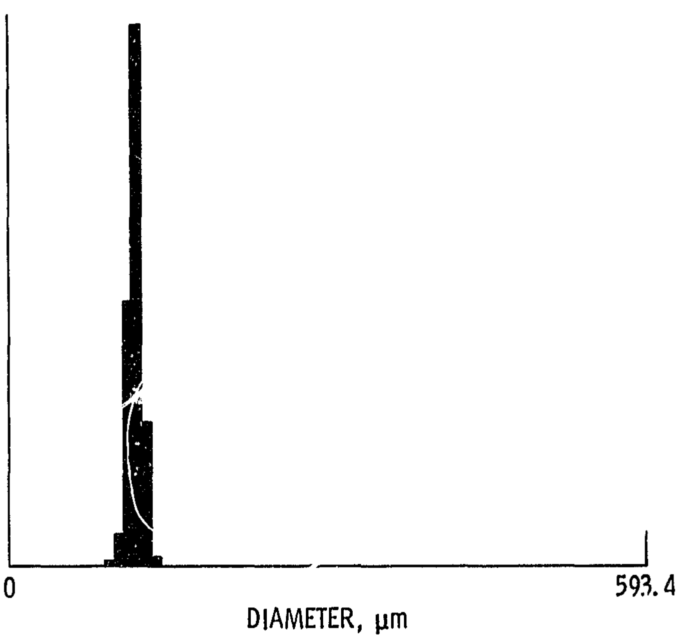


B - L SIZE: 129.5 microns
MEAN SIZE: 125.9 microns
FRINGE SPACING = 26.02 microns
SAMPLES = 500

(a) Sample of data from measurements of a monodispersed droplet stream without beam interference.



B - L SIZE: 129.5 microns
MEAN SIZE: 122.3 microns
FRINGE SPACING = 26.02 microns
SAMPLES = 2092

(b) Sample of data from measurements of a monodispersed droplet stream with additional spray introduced in the beam paths.

Figure 12. - Size distribution of a monodispersed string of droplets using the phase detection technique.

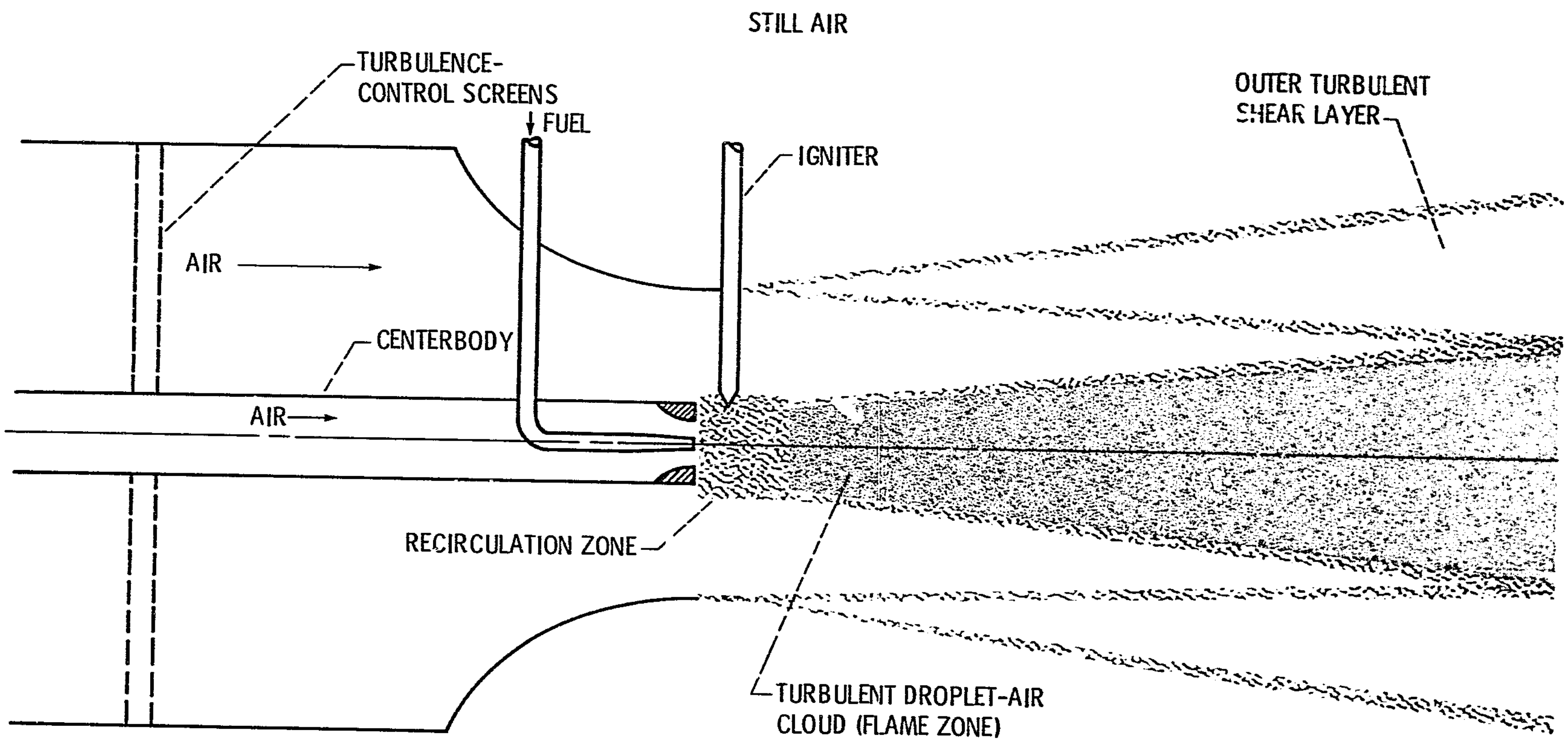


Figure 13. - Schematic of co-axial freejet apparatus which will be used to produce a benchmark spray combustion experiment for application of modern laser diagnostic techniques.